SLEPTONS: MASSES, MIXINGS, COUPLINGS [*]

A. FREITAS[a], H.-U. MARTYN[b], U. NAUENBERG[c], P. M. ZERWAS[d]

[a] *Fermi National Accelerator Laboratory, Batavia, IL 60510-500, USA*
[b] *I. Physikalisches Institut, RWTH Aachen, D-52074 Aachen, Germany*
[c] *University of Colorado, Boulder, CO 80301, USA*
[d] *Deutsches Elektronen-Synchrotron DESY, D–22603 Hamburg, Germany*

This presentation summarizes recent work of different groups on the analysis of slepton parameters at a TeV linear collider. In particular, measurements of the masses, mixings and Yukawa couplings for the neutral and charged sleptons of the first/second generation and for the charged slepton sector of the third generation are reviewed. For all relevant processes, threshold corrections and higher order corrections in the continuum are available, thus allowing high-precision analyses of the parameters in the slepton sector.

1 Overview

The analysis of the supersymmetric particle sector at future colliders entails a diverse and challenging experimental program for the measurement of masses, mixings and couplings. It is imperative to scrutinize accurately the fundamental symmetry relations of supersymmetry (SUSY), which are expressed in the identity of gauge couplings (g) and the SUSY Yukawa couplings ($\hat{g}$) between fermions, sfermions and gauginos. In addition, the precise determination of SUSY breaking parameters from sparticle mass and mixing measurements establishes the basis for reconstructing the fundamental breaking mechanism at possibly very high energy scales [1].

The SUSY partners of the leptons, sleptons, can best be studied at a future high-energy $e^{\pm}e^{-}$ linear collider. The masses of the sleptons can be extracted from measurements of the energy distributions of their decay products or from scans of the cross-sections at the pair production threshold. From the analysis of the production cross-sections in the continuum, the couplings and mixings of the sleptons can be determined. In this report, recent advances in understanding the physics of sleptons will be summarized, with particular focus on new developments for the neutral sleptons (sneutrinos) and the third generation sleptons (staus). For a review of earlier slepton studies, see *e.g.* Ref. [2].

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	Mass	Width	Decay modes		
$\tilde{l}_R^\pm = \tilde{e}_R^\pm/\tilde{\mu}_R^\pm$	142.7	0.21	$l^\pm \tilde{\chi}_1^0$ 100%		
$\tilde{l}_L^\pm = \tilde{e}_L^\pm/\tilde{\mu}_L^\pm$	202.3	0.25	$l^\pm \tilde{\chi}_1^0$ 48%	$l^\pm \tilde{\chi}_2^0$ 19%	$\nu_l \tilde{\chi}_1^\pm$ 33%
$\tilde{\tau}_1^\pm$	133.2	0.20	$\tau^\pm \tilde{\chi}_1^0$ 100%		
$\tilde{\tau}_2^\pm$	202.3	0.34	$\tau^\pm \tilde{\chi}_1^0$ 53%	$\tau^\pm \tilde{\chi}_2^0$ 17%	$\nu_\tau \tilde{\chi}_1^\pm$ 30%
$\tilde{\nu}_l = \tilde{\nu}_e/\tilde{\nu}_\mu$	186.0	0.16	$\nu_l \tilde{\chi}_1^0$ 87%	$\nu_l \tilde{\chi}_2^0$ 4%	$l^- \tilde{\chi}_1^+$ 10%
$\tilde{\nu}_\tau$	185.1	0.15	$\nu_\tau \tilde{\chi}_1^0$ 89%	$\nu_\tau \tilde{\chi}_2^0$ 3%	$\tau^- \tilde{\chi}_1^+$ 8%
$\tilde{\chi}_1^0$	96.2	—	—		
$\tilde{\chi}_2^0$	176.6	0.020	$\tilde{e}_R^\pm e^\mp$ 6%	$\tilde{\mu}_R^\pm \mu^\mp$ 6%	$\tilde{\tau}_1^\pm \tau^\mp$ 88%
$\tilde{\chi}_1^\pm$	176.1	0.014	$\tilde{\tau}_1^+ \nu_\tau$ 100%		

Table 1: Masses, widths (in GeV) and main decay branching ratios of sleptons and of light neutralino and chargino states in their decay chain for the reference point SPS1a.

In many SUSY breaking scenarios the sleptons are relatively light, leading to simple decay signatures involving light neutralino/chargino states and leptons. Tab. 1 summarizes the most important decay modes in the SPS1a scenario [3]. The production of sleptons of the second and third generation in e^+e^- collisions proceeds through s-channel photon and Z-boson exchanges in P-waves with a characteristic rise of the excitation curve $\propto \beta^3$ with $\beta = (1-4m_{\tilde{l}}^2/s)^{1/2}$. The production of selectrons [2] and electron-sneutrinos proceeds in addition through t-channel neutralino or chargino exchange, respectively. Selectrons can also be produced in e^-e^- collisions. Due to the Majorana nature of the neutralinos, some selectron channels are generated in S-waves, with a steep threshold excitation $\propto \beta$, namely for $\tilde{e}_R^\pm \tilde{e}_L^\mp$ pairs in e^+e^- annihilation and $\tilde{e}_R^- \tilde{e}_R^-, \tilde{e}_L^- \tilde{e}_L^-$ pairs in e^-e^- scattering.

2 Theoretical Picture

The steep rise of the slepton excitation curves allows the very precise determination of the slepton masses (see next section). It is necessary therefore to include effects beyond leading order in the theoretical prediction [4,5]. Non-zero width effects play an important role near threshold and can be incorporated by shifting the slepton mass to the complex plane, $m_{\tilde{f}}^2 \to m_{\tilde{f}}^2 - im_{\tilde{f}}\Gamma_{\tilde{f}}$. To keep the amplitude gauge-invariant, the signal contribution with two resonant sleptons, $ee \to \tilde{f}\tilde{f} \to ff\tilde{\chi}\tilde{\chi}$, $f = e, \mu, \tau, \nu$, must be supplemented by other non-resonant

diagrams leading to the same final state $ff\tilde{\chi}\tilde{\chi}$. The production cross-sections for charged sleptons receive large corrections near threshold from Coulombic photon exchange between the slowly moving sleptons. Beamstrahlung and initial-state radiation also modify the excitation curves substantially.

For slepton production in the continuum, $i.e.$ sufficiently far above the threshold, one can assume, to good approximation, on-shell production of the slepton and thus factorize their decay. The cross-sections and polarization asymmetries can be significantly modified by higher-order corrections. For all production processes the most important decay modes, complete one-loop corrections are available: in Ref. [5] the $\mathcal{O}(\alpha)$ corrections to smuon, selectron and sneutrino production were presented, while stau production, including mixing effects, has been analyzed in Ref. [6]. The slepton decays to leptons and neutralinos or charginos were calculated at $\mathcal{O}(\alpha)$ in Ref. [7].

For a full one-loop analysis, these individual calculations have to be combined within a framework that uniquely defines the SUSY parameters beyond tree-level. Such a comprehensive study is currently pursued within the SPA Project [8,9]. In the "SPA Convention" all heavy particle masses and lepton masses are defined on-shell, while the MSSM Lagrangian parameters are given in the $\overline{\text{DR}}$ scheme at the scale $\tilde{M} = 1$ TeV. This provides the basis from which all other parameters, $e.g.$ the neutralino/chargino masses and mixings, can be calculated at one-loop level in any given scheme as part of the higher-order cross-section and decay width calculations [10]. As an example, Fig. 1 shows the radiative corrections to selectron pair production, $e^-e^- \to \tilde{e}^-\tilde{e}^-$ and electron-sneutrino pair production, $e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e^*$, for the SPS1a scenario [3].

3 Experimental Methods: Masses, Mixings, Couplings

Based on the characteristic decay of sleptons into neutralinos, $\tilde{l} \to l\,\tilde{\chi}_1^0$, both the masses of the slepton and neutralino can be determined from measuring the upper and lower edges of the decay lepton spectrum [11], see Fig. 2 (a). The accuracy of such an analysis is limited due to the high correlation between the slepton and neutralino mass dependence. The analysis of sneutrinos is more involved for models with light sneutrinos, such as SPS1a, since in such scenarios most sneutrinos decay into invisible channels [b], see Tab. 1. The $\tilde{\nu}$ mass resolution could be optimized by focusing on the channel where one sneutrino decays invisibly, while the other decays into a chargino, $e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e^* \to \nu_e\tilde{\chi}_1^0\,e^\pm\,\tilde{\chi}_1^\mp$ [13], see Fig. 2 (b).

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[b]If the sneutrinos are even lighter than the $\tilde{\chi}_1^\pm$ charginos, leading to completely invisible sneutrino decays, the exciting opportunity opens up to study the sneutrino properties through the lepton spectrum of the chargino decays [12].
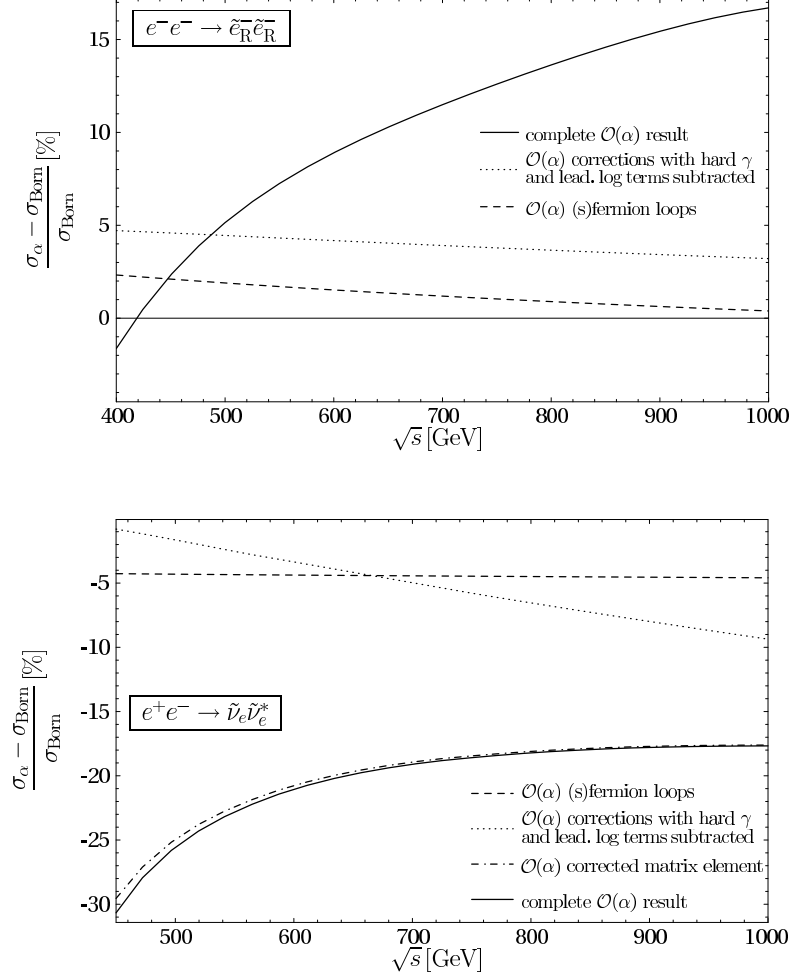
Figure 1: $\mathcal{O}(\alpha)$ corrections to the cross-sections for $e^+e^- \to \tilde{e}_R^- \tilde{e}_R^-$ and $e^+e^- \to \tilde{\nu}_e \tilde{\nu}_e^*$ relative to the Born cross-sections. Besides the full $\mathcal{O}(\alpha)$ result, contributions from different subsets of diagrams are shown, in particular the genuinely process-specific corrections defined by subtracting hard photon radiation and leading-log soft and virtual photon effects from the overall $\mathcal{O}(\alpha)$ corrections. The shift between the lower two curves in the $\tilde{\nu}_e$ panel results from the one-loop correction to the sneutrino mass.
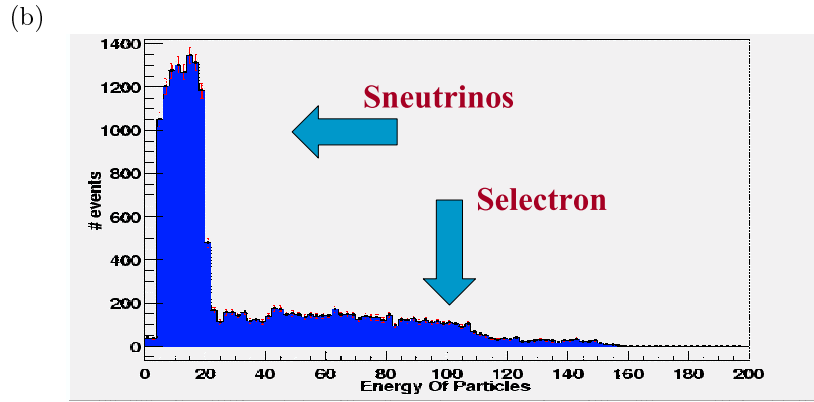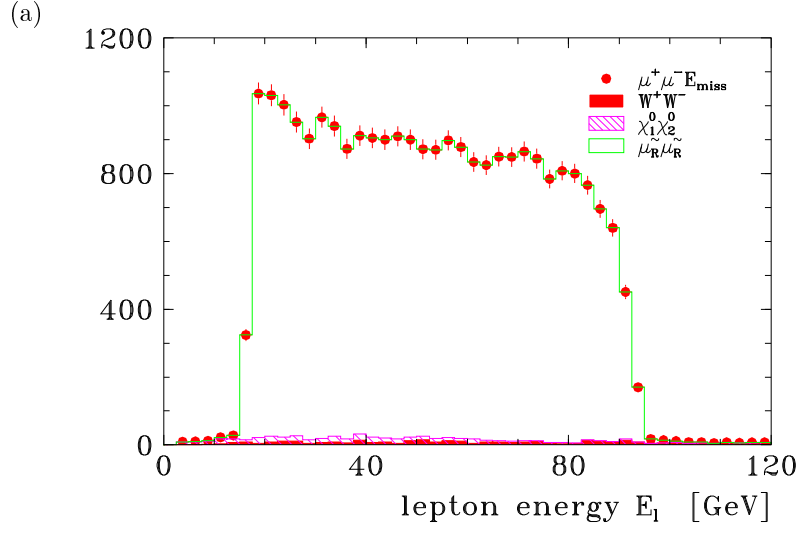
(a)

(b)

Figure 2: Charged lepton energy spectra for (a) $e^+e^- \rightarrow \tilde{\mu}_R^+ \tilde{\mu}_R^-$, $\tilde{\mu}_R^\pm \rightarrow \mu^\pm \tilde{\chi}_1^0$, and for (b) $e^+e^- \rightarrow \tilde{\nu}_e \tilde{\nu}_e^* \rightarrow \nu_e \tilde{\chi}_1^0 e^\pm \tilde{\chi}_1^\mp \rightarrow e^\pm \mu^\mp + \not{\!\!E}$ including background selectron production.

	m [GeV]	Δm [GeV]			Γ [GeV]
		spectra	thr. scans	combined	
$\tilde{\chi}^0_1$	96.1	0.10	–	0.065	–
$\tilde{e}_R$	143.0	0.08	0.05	0.05	0.21 ± 0.05
$\tilde{e}_L$	202.1	0.8	0.2	0.2	0.25 ± 0.02
$\tilde{\nu}_e$	186.0	1.2	1.1	1.1	< 0.9
$\tilde{\mu}_R$	143.0	0.2	0.2	0.085	0.2 ± 0.2
$\tilde{\mu}_L$	202.1	–	(0.5)		
$\tilde{\tau}_1$	133.2	0.3			
$\tilde{\tau}_2$	206.1		(1.1)		

Table 2: Expected accuracies Δm for slepton mass measurements via decay energy spectra (3rd column) and threshold scans (4th col.) in the SPS1a scenario. The combined values (5th col.) are based on using the threshold R-selectron mass measurement as input for the decay spectrum analyses to reduce correlation effects. The threshold scans are also sensitive to the slepton widths Γ (6th col.). The numbers in parentheses are estimates. Void entries have not been analyzed yet; barred entries cannot be accessed in the reference point SPS1a.

Alternatively, the slepton masses can be determined from a scan of the characteristic excitation curves for pair production near threshold, leading in many channels to a precision superior to the decay spectrum analysis [5]. In addition, one can use the extremely precise determination of the R-selectron mass of $\Delta m_{\tilde{e}_R} = 50$ MeV from the threshold scan in $e^- e^-$ collisions as an input for the analysis of the selectron decay energy spectrum, in order to obtain a more accurate determination of the lightest neutralino mass. This information is summarized in Tab. 2. The numbers in parantheses are estimates from Ref. [14].

Among the charged sleptons of the third generation, large mixing effects are expected. While the stau masses can be determined using the same methods as described above, the stau mixing angle $\theta_{\tilde{\tau}}$ can be extracted from two cross-section measurements $\sigma[e^+e^- \to \tilde{\tau}_1 \tilde{\tau}_1]$ with different beam polarizations, see Fig. 3, Ref. [15]. In the SPS1a scenario one obtains $\cos 2\theta_{\tilde{\tau}} = -0.84 \pm 0.04$, i.e. a precision is achievable at the per-cent level [11]. The value of the mixing angle and the degree of τ polarization in $\tilde{\tau}_1$ decays depends on the fundamental parameters μ, A_τ and $\tan\beta$ in the Lagrangian, which can therefore be constrained by these measurements. Since in a scenario with $\tan\beta \gtrsim 10$, charginos and neutralinos in the decay chain will dominantly lead to additional tau leptons in the final state, it is very difficult to disentangle the heavier $\tilde{\tau}_2$ from the background of the lighter $\tilde{\tau}_1$. The $m_{\tilde{\tau}_2}$ measurement is therefore still an open problem.

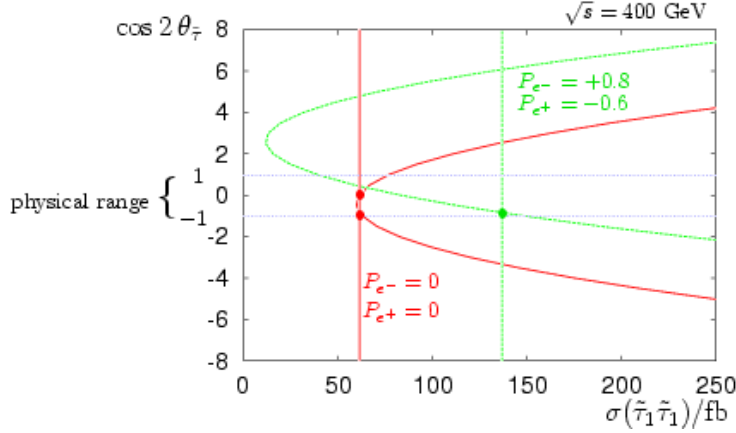The production cross-sections of the first generation sleptons are sensitive

Figure 3: *Mixing angle* $\cos 2\theta_{\tilde{\tau}}$ *versus cross section* $\sigma(e^+e^- \to \tilde{\tau}_1\tilde{\tau}_1)$ *at* $\sqrt{s} = 500$ *GeV for beam polarisations* $P_{e^-} = +0.8$ *and* $P_{e^+} = -0.6$ *(green/light) and the unpolarised case (red/dark). The vertical lines indicate the predicted cross sections.*

to the SUSY Yukawa couplings between a selectron/sneutrino, electron and neutralino/chargino, $\hat{g}(e\tilde{e}\tilde{\chi}^0)/\hat{g}(e\tilde{\nu}_e\tilde{\chi}^\pm)$. From the measurement of the $\tilde{e}_{\rm R}$, $\tilde{e}_{\rm L}$ and $\tilde{\nu}_e$ cross-sections one can therefore test the fundamental SUSY identity between the gauge couplings g and the corresponding gaugino Yukawa couplings $\hat{g}$ in the electroweak sector. For selectron production, beam polarization is crucial for disentangling the SU(2) and U(1) Yukawa couplings. Taking into account uncertainties from the selectron mass and the neutralino parameters, the SU(2) and U(1) Yukawa couplings, $\hat{g}$ and $\hat{g}'$, can be extracted with a precision of 0.7% and 0.2%, respectively, at a 500 GeV collider with 500 fb^{-1} integrated luminosity in the SPS1a scenario [5]. Sneutrino production is only sensitive to the SU(2) coupling $\hat{g}$. Here the dominantly invisible decay of the sneutrinos limits the expected precision, resulting in an error of 5% [5] in the SPS1a scenario.

4 Conclusions

The slepton sector is so far the best understood SUSY sector, both theoretically and experimentally. It has been shown in experimental simulation analyses that all relevant slepton parameters can be measured at a linear collider with per-cent or even per-mille accuracy. The theoretical calculations for the cross-sections are under control only at the per-cent level, so that much more work on the theoretical side is needed to match the experimental accuracy.

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With all tools in place, the fundamental identity between gauge and Yukawa couplings can be precisely tested and the accurate determination of the SUSY mass parameters and mixings opens up a window to the understanding of the underlying fundamental supersymmetric theory and the breaking of supersymmetry.

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